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ROCK/ELASTOMER COMPOSITES AS IMPACT RESISTANT MATERIALS

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ABSTRACT

Composites cast from polymers, rock aggregates and sand have been examined to determine their resistance to penetration by 7.62mm diameter high velocity projectiles. The effects of using different polymer and rock aggregate types have been invesitgated, and the resultant composites optimized in terms of cost effectiveness and penetration resistance.

Optimization was carried out using response surface theory and variables considered were mix proportions, rock aggregate particle size and polymer hardness. Penetration tests were carried out on optimized composites to determine the thickness required for a given confidence level of projectile containment.

INTRODUCTION

An interest in the protection of buildings and other structures against small arms fire led Gibbs and Prescott (1) to undertake a limited experimental study into the behaviour of dry gravel armour which had been used in wire mesh boxes to protect vehicles against infantry fire during World War II. Their tests showed that a theoretical approach to find the optimum gravel particle size, using "billiard ball" theory, was not valid because of the high degree of comminution of the gravel particles. The effectiveness of the armour, however, was proven.

A major problem in using gravel is containment of the material. A flexible binder is desirable because of the extensive fracture which occurs in brittle material on impact. Hence the idea arose of using a cold curing rubbery polymer as the binder, and a study has been carried out to test the effectiveness of this type of rock/elastomer composite and to optimize the material in terms of its impact resistance.

At an early stage it was realised that a two phase mixture of elastomer and rock particles would be very expensive because of the large percentage voids which had to be filled with high cost elastomer. Hence sand was included in the mix to act as a filler. The resulting composites were unusual because of the relatively low elastic modulus of the matrix materials. No published information on the penetration resistance of this type of composite material could be found, although there was considerable information about penetration into homogeneous and layered materials (2, 3, 4).

Descriptions of penetration mechanics have used the following approaches (i) empirical, (ii) assumed force law, (iii) analytical and (iv) numerical (using computer codes). In the first two categories the parameters must be determined from penetration experiments, and application of the resultant formulae is not valid in any other context. This is because the parameters are not defined explicitly in terms of the constitutive properties of the medium and projectile characteristics. However, such methods usually show good results within these bounds.

In the analytical approach, constitutive and continuum equations are used to describe the event, and, ideally, are solved in a closed form to produce predictions of depth of penetration, projectile decleration, etc. However, this type of solution has not been achieved without a high degree of simplification.

Numerical approaches are expensive in time and money. However, for situations using materials with well defined properties offering a high degree of reproduceability, their value is apparent.

The latter two methods have only been developed to the stage where they can cope with homogeneous materials, possibly in layers. Heterogenous materials such as concrete have been considered, but have been treated as homogeneous. Generally, the projectile sizes used have been orders of magnitude larger than the concrete aggregate size. In the case of the composites in this study, the aggregate size was similar or about one order of magnitude larger in terms of mass than the projectile. This meant that the situation could not realistically be simplified as homogenous or layered. Because of these difficulties an experimental, rather than analytical, approach was adopted.

TEST MATERIALS

The composites were produced by mixing various proportions of sand filler, rock aggregate and elastomer.

Sand Filler

The sand filler reduced the amount of elastomer required to fill the void spaces between the rock aggregate particles. The effect of the sand particle size on penetration resistance was considered insignificant, so Zone II or Zone III sand as defined by British Standard 882 : Part 2 (5) was used in all composites.

Rock aggregate

An advantage of the composites being examined is that they are fairly economical because locally available aggregates may be used. To examine the influence of aggregate type on the penetration resistance of the composite, the main series of tests were carried out using three different aggregates: crushed limestone, crushed basalt, and river gravel.

The crushed limestone was a fine grained sedimentary rock, mid grey in colour and angular in shape with a significant amount of dust present. The crushed basalt was a fine grained olivine basalt, dark greyish green in colour and angular in shape with a significant amount of dust present. Most of the dust in these crushed rock aggregates was removed by sieving prior to mixing with the sand filler and elastomer.

The river gravel was predominately quartzite and quartz, with small proportions of other rock types. The particles of the predominant rock types were rounded or irregular, but the minority rock type particles were of all shapes. Very little dust was present, because of the aggregate's mode of deposition from moving water which carried away the fines.

The properties of these rock aggregates as defined in British Standard 812 (6) are listed in Table 1. Also included in this Table are the percentage voids for 27.5 - 37.5mm aggregate found using 300mm dia. x 300mm high cylindrical moulds as recommended in the British Standard, and using 152mm cube moulds similar to those used for composite specimen preparation.

	Crushed Limestone	Crushed Basalt	River Gravel
Oven dry specific gravity	2.67	2.75	2.57
Aggregate crushing value, %	23	17	-
Aggregate impact value, %	23	17	16
10% fines load (kN)	160	250	377
% voids - compacted B.S. cylinder test	43%	43.8%	35%
% voids - uncompacted B.S. cylinder test	49.3%	49.4%	39.4%
% voids - uncompacted 152mm cube mould	52.1%	49.4%	43.7%
% voids - compacted 152mm cube mould	44%	46%	39.1%

Table 1 Rock aggregate properties

Elastomer

To achieve a relatively inexpensive composite which could be produced without special curing facilities and have a satisfactory penetration resistance within, at most, twenty four hours, it was essential to find an elastomer which satisfied a number of criteria. The elastomer had to be commercially available in large quantities at relatively low cost. For ease of mixing and casting it had to have a low viscosity and a gel time sufficiently long for casting. Thereafter it had to cure quickly at ambient temperature.

To act as a flexible binder at impact and during penetration the elastomer had to be elastic at high rates of strain. It also had to give a composite with adequate mechanical properties for large panels to be produced as cladding material or to form free standing units to a reasonable height.

Initially a wide range of cold cure thermosetting polymers including epoxy resins, natural and synthetic rubbers and polyurethanes were examined. None of the sixteen polymers tested initially satisfied all of the criteria listed for the ideal elastomer. Polyurethanes were found to satisfy most of the criteria and two polyurethanes, a polyester polyurethane (Polymer A) and a blend of two polyether polyurethanes (Polymer B) were chosen for the main investigation. By varying the proportions of the polymer constituents different hardnesses of cured elastomer could be achieved.

SPECIMEN PREPARATION

Single size rock aggregate was used in all specimens and after sieving, the aggregate and sand filler were oven dried. Mixing was carried out using a mechanical bowl mixer. The elastomer constituents were mixed for about 30 seconds to ensure complete blending and then the rock aggregate and sand filler were added to the resin and the mixing continued for a further minute. The composite was cast in layers in 152mm concrete cube moulds, each layer being tamped in a consistent manner. Polymer A composites could be demoulded 1½ hours after casting and Polymer B composites 1 hour after casting.

TEST METHOD

Test specimens with 152mm square face and varying thicknesses were fixed in a target holder which provided support round the rear perimeter of the specimen but with minimal lateral restraint.

Projectiles were either 7.62mm NATO ball ammunition (mass 9.3g with lead alloy core) or 7.62mm NATO Armour Piercing ammunition (mass 9.6-9.9g with hardened steel core). Initially both types of ammunition were used, but indications were that armour piercing projectiles penetrated further than ball projectiles. Armour piercing projectiles were therefore used in the main test series and after the composites had been optimized a subsidiary series of tests using ball ammunition was carried out on an optimized composite to confirm the lower penetrations.

The projectiles were remotely fired from a fixed pressure housing, bolt and barrel arrangement 20m from the target. A photodiode type velocity measuring rig was mounted 1.5m in front of the target and this allowed the projectile velocity to be checked. Mean measured velocity for ball ammunition was 794 m/s and for armour piercing ammunition 807 m/s.

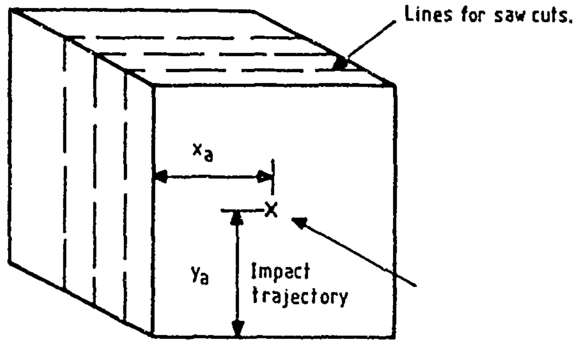
After testing target specimens were sectioned as shown in Figure 1(a). This enabled the penetration depth of the projectile to be determined and the penetration path length could be calculated by taking coordinates as shown in Figure 1(b).

OPTIMIZATION OF THE COMPOSITES

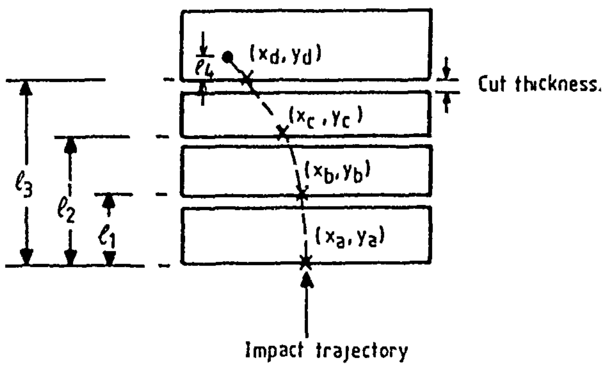
The fundamental aim of the project was to minimise the target thickness necessary to resist perforation, whilst keeping the cure time and the impact damage to the composite to an acceptable level. Thus the normal penetration depth, D, or penetration path length, D', were considered as alternatives for the design criterion. Initially the former was used but preliminary impact tests on composites showed that the penetration path rarely remained straight and normal to the impact face. The penetration path length was thus of more significance in assessing resistance than the penetration depth, and was therefore used as the design criterion in the main series of tests.

In attempting to optimize the composites in terms of their penetration resistance there was a large number of independent variables which had to be considered for each rock aggregate/elastomer combination. These variables are listed in Table 2. It was decided to concentrate the main test programme on the four primary quantitative (x) variables at the top of Table 2, and to keep the other secondary variables constant.

Normally the optimization procedure for four variables would be carried out by keeping three variables constant and varying the fourth. This would be repeated for each of the primary variables in turn. Thus sets of fitted equations



(a) ISOMETRIC ELEVATION ON IMPACT FACE



(b) PLAN ON SECTIONED SPECIMEN.

Fig. 1 Target sectioning

Variable	Values in optimization programme
% polymer by weight in mix, x_1	variable (7%-17%)
% rock aggregate by weight, x_2	variable (44%-64%)
% sand filler by weight in mix	variable (19%-49%)
rock aggregate, x_3 mm	variable (9.5-37.5)
polymer hardness, x_4 Shore A°	variable (60-85)
specimen cure temperature, °C	ambient
specimen test temperature, °C	ambient
age of specimen, days	1 day
specimen thickness, mm	152mm
bullet velocity, m/s	approx. 800 m/s

Table 2 Quantitative independent variables

would be obtained, each in only one x variable. From this stage, optimization can only be achieved by examining general trends and carrying out experiments on a trial and error basis. This method may require a very large number of tests and the inter-dependence of the variables may not be appreciated.

These difficulties were overcome by using a statistical method known as response surface theory, the general principles of which have been described by Cochran and Cox (7). Details of the application of this theory to the optimization of rock/elastomer composites are given by Anderson et al (8), and the mixes obtained from the optimization procedures are given in Table 3.

THICKNESS TESTS

During the optimization test series targets which were expected to be sufficiently thick (152mm) to prevent perforation were used. Very occasionally perforation occurred when the worst combination of primary variables was used, but no perforations were recorded with optimum mixes. When each of the optimum mixes had been identified it was necessary to determine the specimen thickness, t_m, which would contain the projectile with a given degree of confidence.

Two confidence levels were examined for the protective capability of the composite. The first, 80-90% containment, was thought to be applicable where the composite was to be used for protecting an existing reasonably strong structure, e.g. brickwork. Most of the projectiles would be contained, but those that were not would have their kinetic energy greatly decreased. The second confidence level, 97.5-99%, was considered sufficient where the composite was to be used alone, or over a weak structure.

Using specimens of varying thickness of optimized composites it was possible to estimate a thickness for each composite at which 80-90% containment would be achieved. Series of 20 tests on identical optimized specimens of this thickness were then carried out to check the 80-90% confidence level and to predict thickness for 97.5%-99% confidence. These tests showed that some adjustment of the mixes obtained from the main optimization test series was required for the Polymer B/basalt and Polymer B/limestone composites. Details of these tests and the various mix adjustmenets have been described by Anderson et al (8), and the results of thickness tests on all the final mixes are summarised in Table 4.

Polymer type	Rock type	% polymer by weight x_1	% rock aggregate by weight x_2	Rock size (mm) (nominal) x_3	Polymer hardness (Shore A°) x_4
A	River gravel	9	60	26.5 - 37.5	75
B	River gravel	9.8	59	26.5 - 37.5	80
B	Basalt	7	56	26.5 - 37.5	80
B	Limestone	7	64	26.5 - 37.5	80

Table 3 Mixes obtained from optimization procedure

Polymer type	Rock type	% Polymer by weight x_1	% rock aggregate by weight x_2	Rock size (mm) x_3	Polymer hardness (Shore A°) x_4	t_m for 80-90% confidence limits (mm)	t_m for 97.5-99% confidence limits (mm)
A	River gravel	9	60	26.5 to 37.5	75	90	115
B	River gravel	9.8	59	26.5 to 37.5	80	75	100
B	Basalt	9	58	26.5 to 37.5	80	110	140
B	Limestone	11	59	26.5 to 37.5	80	100	130

Table 4 Summary of results from thickness tests

SUPPLEMENTARY TESTS

Target Temperature Effects

In practical use the composite may be subjected to extremes of temperature and because the elastomer is very temperature sensitive, it was felt prudent to examine the protective capabilities of one of the optimized combinations (river gravel/Polymer B) at temperatures other than ambient. Three series of twenty tests each were carried out three days after casting on identical specimens 80mm thick (80-90% confidence level). In the first series specimens, after curing, had been cooled in a freezer and the average specimen temperature at testing was -7°C. In the second series specimens were heated in an oven after curing and tested at a mean temperature of +34°C. The third series of tests was carried out on specimens cast, cured and tested at ambient temperature (+15°C). The results of the tests showed that higher than ambient temperatures had little effect on penetration resistance, but a low temperature increased the resistance. This increase in resistance was accompanied by increased brittleness of the target with much greater damage around the impact zone.

Contact Explosive Tests

A limited series of tests was carried out to examine the resistance of rock/elastomer composites to small explosive charges. Slabs 610mm x 610mm x 80mm of optimum mix of the best composite (river gravel/Polymer B) were cast and cured. Similar slabs of concrete were cast with the same proportions and size of river gravel and sand as in the composite slabs.

The slabs were placed on a steel sheet on the ground and a hemispherical charge of plastic explosive was detonated centrally in contact with the slabs. By trial and error the minimum charge required to defeat the slabs, i.e. cause disintegration, was determined.

The results showed clearly the superior performance of the composite over concrete. A 50g charge caused only cratering of the composite slab with no cracking, indicating a high tensile resistance in the composite. A similar charge detonated on a concrete slab caused complete disintegration of the slab. Concrete was defeated by a 12.5g charge whereas the minimum charge necessary to defeat the composite was 150g.

COMMENTS

The tests showed that composites formed by binding rock aggregate together with an elastomeric matrix were effective in stopping small arms fire. The effectiveness of the composite depends on the constituents and the best performances were found with composites containing Polymer B. With all composites the optimized material contained the largest size gravel (26.5-37.5mm) which could easily be mixed with the resin and sand filler.

The aggregate type affects the penetration resistance. In particular, the harder the rock (as described by aggregate impact value) and the denser the rock particle packing (described by percentage voids), the greater will be the composite resistance. A guide to the necessary thickness of composite for any rock aggregate and for any particular confidence level is given in Table 5. It is suggested that the mix should contain 10% by weight of Polymer B (hardness 80 Shore A°), 60% rock aggregate of the largest available (up to 40mm maximum) and 30% sand. Rocks with aggregate impact values greater than 25 should not be used.

Confidence level	Aggregate impact value between 25 and 15	Aggregate impact value less than 15
80%	110mm	95mm
90%	120mm	105mm
95%	130mm	115mm
97.5%	140mm	120mm
99%	150mm	130mm

Table 5 Suggested thickness of composite containing untested rock aggregate

A major advantage of these composites is their early resistance to penetration. The material has sufficient cohesion for moulds to be removed after 1 - 1½ hours. Static compression, bending and creep tests indicated full strength was achieved about eight hours after casting. These static tests also showed that the composite was strong enough for 80mm thick panels up to 3m square to be handled, or for the material to be free standing to a height of 10 metres.

The limited series of explosive tests showed promising results and this aspect of material behaviour should be further investigated.

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